BY PHIL ZUK • FAIRCHILD SEMICONDUCTOR

Designing offline power supplies using power-factor correction

BY REDUCING AC-LINE CURRENT, SWITCHED-MODE POWER SUPPLIES THAT INCORPORATE PFC ARE CUTTING THE COST OF INSTALLING AND OPERATING AC-POWERED EQUIPMENT. INCREASINGLY, REGULATORY BODIES ARE REQUIRING PFC.

To develop offline power supplies that use PFC (power-factor correction), you must first understand the meaning of PFC and the regulations that surround the design of offline power supplies.

PFC aligns the current waveform with the voltage waveform. If the voltage and current waveforms are not aligned, the PF (power factor) is less than 1 (**Figure 1**); otherwise, the PF is equal to 1 (**Figure 2**). In most cases, PF-corrected designs have PFs of 0.95 to 0.98. Most supplies that are not PF-corrected have PFs of approximately 0.6. In a three-phase system, if the voltage and current waveforms are not aligned, nonsinusoidal currents at three times the line frequency flow in the neutral line, requiring companies that supply ac power to use larger neutral conductors than would otherwise be necessary and to install more capacity to produce the required number of kilovolt-amperes. These harmonics are tough on power systems and can lead to overload and overheating of transformers, capacitor banks, and other power-system elements, sometimes tripping circuit breakers.

With this basic understanding of PFC, your next step is to determine when to use the PFC technique to comply with regulations in the regions where the product you are designing will be used. In 2001, the European Union put into effect EN 61000-3-2 to establish limits on harmonics as high as the 40th of ac-line-powered equipment's input current. Amendment A14, which took effect on January 1, 2001, has eased the impact of power-harmonics requirements in Class D, a group of equipment now defined far more narrowly than in the original standard: PCs, PC monitors, and television sets (**Table 1**).

WHAT CAUSES THE PROBLEM?

On a circuit level, the main cause of PFs of less than 1 in SMPSs (switch-mode power supplies) is that the main capacitor, C_{IN} (**Figure 3**), charges only when V_{IN} is close to V_{PEAK} or

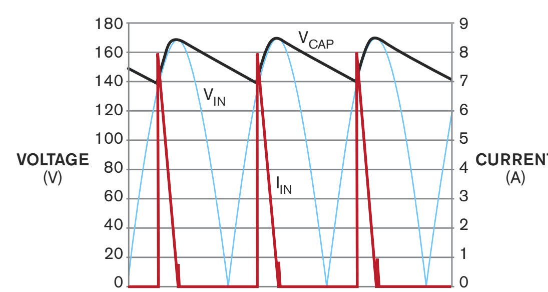

Figure 1 PFC aligns the current waveform with the voltage waveform. If the voltage and current waveforms are not aligned, the PF (power factor) is significantly less than 1.

TABLE 1 EN 61000-3-2 AND AMENDMENT A14 FOR PFC

EN 61000-3-2 Classification Scheme	Amendment A14 Classifications
Class A: balanced three-phase equipment, single-phase equipment not in other classes	Class A: balanced three-phase equipment; household appliances, excluding equipment identified as Class D; tools except portable tools; dimmers for incandescent lamps but not other lighting equipment; audio equipment; anything not otherwise classified
Class B: portable power tools	Class B: no change
Class C: lighting equipment with power requirements greater than 25W	Class C: all lighting equipment except incandescent-lamp dimmers
Class D: not Class B or C, single-phase, not motor driven, requiring less than 600W, and possessing a special waveshape	Class D: single-phase, requiring 75 to 600W, PCs, PC monitors, TV receivers

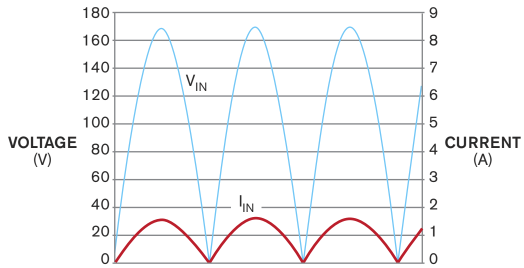

Figure 2 If the voltage and current waveforms are aligned, PF is 1.

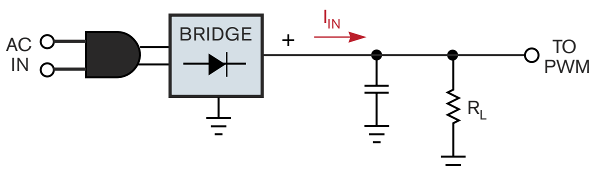

Figure 3 The input to a non-power-factor-corrected SMPS is typically a rectified sine wave.

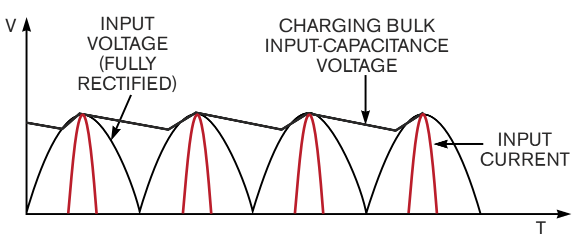

Figure 4 The bulk capacitor charges during the relatively brief portion of the ac-line cycle when the rectified voltage exceeds the bulk-capacitor voltage.

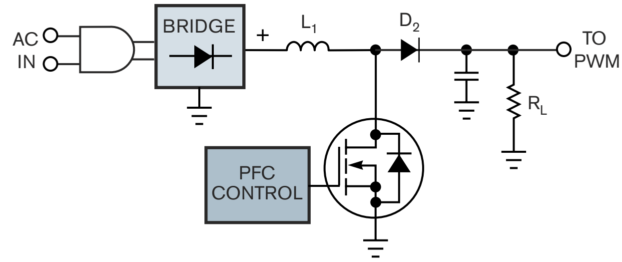

Figure 5 The boost converter adds a series inductor and MOSFET switch to the circuit of Figure 3.

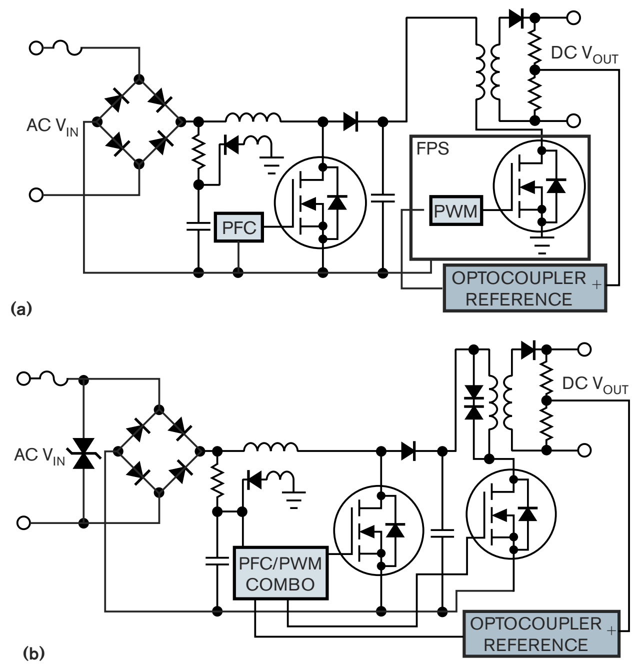

Figure 6 You can design an SMPS with a stand-alone PFC controller (a) or with a combined PFC/PWM-combo controller (b).

when V_{IN} is greater than the capacitor voltage, V_{CIN} (**Figure 4**). To achieve a PF-corrected power output, designers often use a boost converter to maintain a voltage higher than the line voltage's peak value. The boost topology maintains this increased voltage; the PFC controller makes the average inductor current proportional to the input-voltage waveform. The boost topology also allows the average inductor to charge the input capacitor, C_{IN}, now on the output side of the boost controller rather than after the bridge-diode device (**Figure 5**).

Several IC manufacturers provide PFC boost converters. For example, Fairchild offers discontinuous- and continuous-mode devices. Some of these, such as the FAN7527B, are stand-alone PFC controllers (**Figure 6a**). Others, such as the FAN4803, integrate PFC and PWM operation into one packaged device that supplies more than 500W (**Figure 6b**). This variety allows designers to develop offline power supplies that use fewer components and require less space. These combo devices not only achieve PFC control, but also use flyback, forward, or other types of voltage-conversion topology to convert from large dc voltages, such as 385V dc, to 12V dc.

DISCONTINUOUS OR TRANSITION MODE

Discontinuous-mode controllers, such as the FAN7527B, offer PFC control at output-power levels up to and including 200W. Such devices operate in the discontinuous mode in which the boost converter's MOSFET turns on at zero inductor current and turns off when the current meets the desired input-reference voltage (**Figure 7**). In this way, the input-current waveform follows that of the input voltage and achieves an average inductor current that is in phase with the input voltage.

Compared with continuous-mode devices, discontinuous-mode units have higher I^2R and skin-effect losses, use larger magnetic cores, and require larger input filters because of the larg-

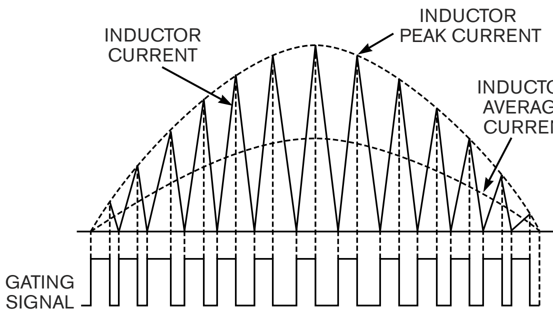

Figure 7 In the discontinuous mode, the boost converter's MOSFET turns on at zero inductor current and turns off when the current meets the desired input-reference voltage.

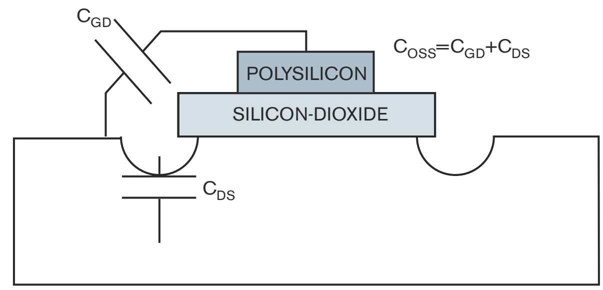

Figure 9 Continuous-mode zero-voltage switching uses an LC-resonant tank circuit to discharge the MOSFET's C_{OSS} (output capacitance).

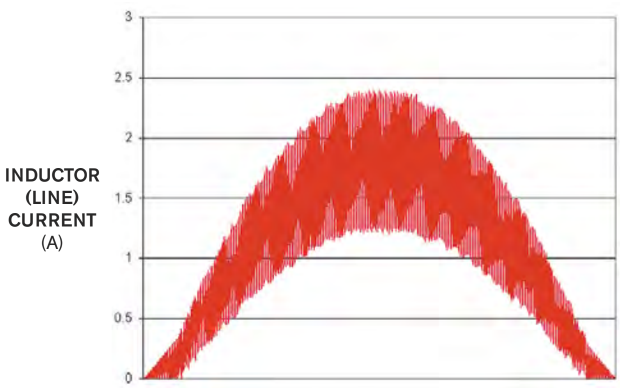

Figure 8 In the continuous mode, the current in the energy-transfer inductor never reaches zero during the switching cycle.

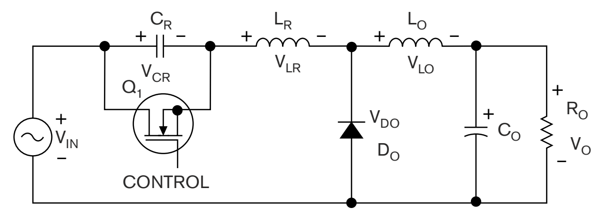

Figure 10 In this ZVS buck converter, when Q_1 turns on, $V_{CR}=V_{DS}=V_{DO}=0$. When Q_1 turns off, the voltage across C_R increases linearly and works with L_R to dissipate the charge stored in C_{OSS}.

er inductor-current swings. On the positive side, use of these devices is less complex because they switch the boost MOSFET on when the inductor current is zero, so the boost diode needs no reverse-recovery-current specification, which allows the use of a less expensive diode. Also, the use of variable switching frequencies spreads the spectrum of the EMI (electromagnetic-interference) signature that results from the boost switch's zero-current turn-on.

Continuous- or hard-switcher modes typically suit SMPS power levels greater than 200W. In this mode, the boost converter's MOSFET does not switch on when the boost inductor is at zero current. Instead, the current in the energy-transfer inductor never reaches zero during the switching cycle (**Figure 8**).

In consequence, the current swing is less than in the discontinuous mode, resulting in lower I^2R losses, lower inductor-core losses, and reduced EMI, which allows the use of a smaller input filter. However, because the MOSFET turns on when the inductor and diode currents are nonzero, a fast reverse-recovery diode is necessary to minimize losses.

CONTINUOUS MODE USING ZVS

Designers can use various techniques to reduce the hard transition of a continuous-mode PFC controller. Fairchild's FAN4822 implements one such technique, ZVS (zero-voltage switching). The primary purpose of using ZVS is to reduce the power loss or power dissipation in the PWM switch during turn-on. More losses occur in the external MOSFET with the increase in switching frequency. This technique uses an LC-resonant tank circuit to discharge the MOSFET's C_{OSS} (output capacitance, **Figure 9**). This capacitance is the sum of the C_{DS} (drain-to-substrate capacitance) and C_{GD} (gate-to-drain capacitance). ZVS works well with power supplies that switch at frequencies greater than 100 kHz. It also reduces the MOSFET's gate-drive requirements because the C_{GD} charge does not exist when the V_{DS} (drain-to-source voltage) equals zero.

When the switch is off, you have a charge, E, on C_{OSS} of $E=1/2C_{OSS}V_{DS}^2$ with $V_{GS}=0V$. Once the switch turns on, this energy dissipates and can become a limiting factor in SMPS topologies. As the switching frequency increases, so does the power dissipation:

$$P_D = E \times f_S,$$

where P_D is the power dissipation, E is the energy stored within C_{OSS}, and f_S is the switching frequency.

In its basic form, ZVS works as follows (**Figure 10**): When switch Q_1 turns on, $V_{CR}=V_{DS}=0$, and $V_{DO}=0$. When switch Q_1 turns off, the voltage across the C_R (resonant capacitor) increases linearly and works with the L_R (resonant inductor) to dissipate the charge stored in C_{OSS}. Note: $L_O>>>L_R$. The voltage

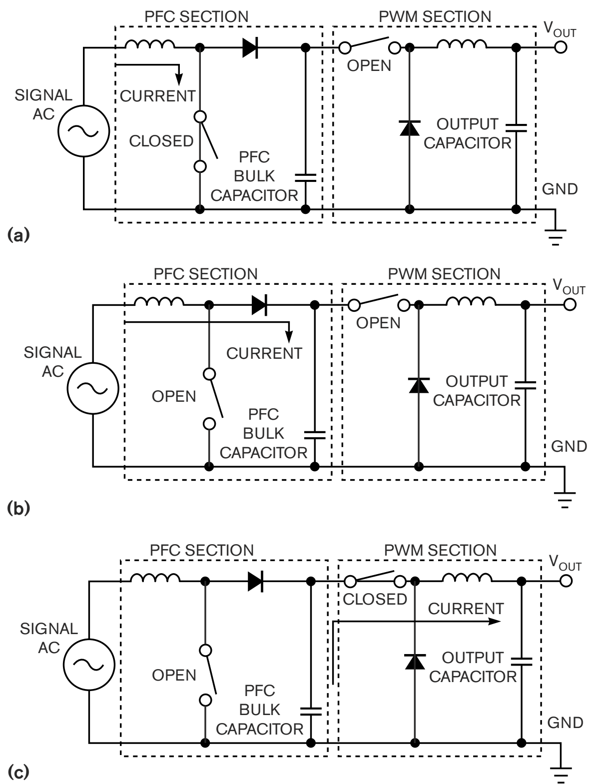

Figure 11 The major steps in the operation of this TEM/TEM converter are energizing the PFC inductor (a), charging the PFC bulk capacitor (b), and powering the output (c).

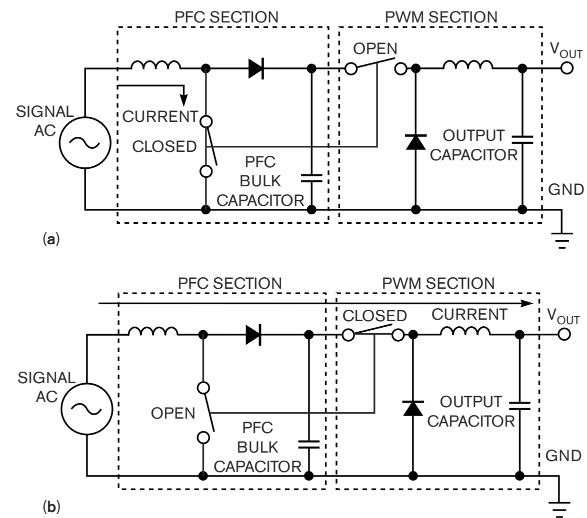

Figure 12 To perform the function of the converter in Figure 11, this LEM/TEM converter needs only two steps: energizing the PFC inductor (a) and charging the PFC bulk capacitor and powering the output (b).

across L_O then reverses polarity, and D_0 begins to conduct, thereby expending the energy stored in L_O. The resonant inductance-capacitance network components, C_R and L_R, are selected based on the maximum input voltage V_{INMAX} and minimum output current I_{OMIN} for the circuit to remain resonant over all operating conditions of line and load.

$$C_R = \frac{1}{Z_R \times \omega_R}; \quad C_R = \frac{I_{OMIN}}{V_{INMAX} \times \omega_R}.$$

$$L_R = \frac{Z_R}{\omega_R}; \quad L_R = \frac{V_{INMAX}}{I_{OMIN} \times \omega_R}.$$

LEM/TEM VERSUS TEM/TEM

In its combo mode (PFC/PWM) devices, Fairchild uses a patented LEM/TEM (leading-edge modulation/trailing-edge modulation) technique, in which the PFC and PWM switches are synchronized so that the PFC switch turns off just as the boost switch turns on. This technique allows the PFC bulk capacitor to be smaller than normal because it does not power the output all by itself; the PFC inductor helps out. Typically, PFC/PWM controllers use TEM/TEM, which results in an additional step as well as a larger PFC bulk capacitor (**Figure 11**).

Figure 11a shows the energizing of the PFC inductor. **Figure 11b** shows the energy from the inductor transferring into the PFC bulk capacitor. When you close the PWM switch, the energy within the PFC bulk capacitor drives the load (**Figure 11c**). Every time this cycle repeats, the PFC bulk capacitor has to be fully charged because it is fully discharged when the PWM switch closes.

In LEM/TEM, the PFC and PWM switches are tied together such that, when one is opening, the other is closing, so when the PFC switch is open, the PWM switch is closed, and vice versa. Initially, when the PFC switch is closed, the PFC inductor is energized. Once the PWM switch is closed, both the output and the PFC bulk capacitor are energized. **Figures 12a** and **12b** show that upon repetition of this cycle, the PFC bulk capacitor does not have to be as large as that in TEM/TEM because it does not power the output all by itself; the PFC inductor helps out.

MORE AT EDN.COM

Go to www.edn.com/ms4122 and click on Feedback Loop to post a comment on this article.

The potential for reducing operating costs by minimizing wasted power explains why device-side PFC has become important in so many products' power systems and is expected to increase the PFC-controller market to \$175 million in 2006. Many standards (for example, EN 61000-3-2) are driving PFs toward 1 and are requiring minimum total-harmonic distortion in systems that consume ever-smaller amounts of power. EDN

AUTHOR'S BIOGRAPHY

Philip Zuk is a staff applications engineer at Fairchild Semiconductor. He has a diploma in electronic engineering technology from Red River College (Winnipeg, MB, Canada) and a bachelor's degree in electrical engineering and a master's in business from the University of Manitoba (Winnipeg). Visit www.fairchildsemi.com/pfc for additional information.